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# PRACTICAL ASPECTS OF DATA PROCESSING AND ENCODING FOR SPACE COMMUNICATIONS

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## 1. INTRODUCTION

Communications from spacecraft can be placed, from one point of view, in either of two general categories: (1) experimental and monitoring data from sensors on the spacecraft to provide measurements of the space environment and on the condition of the spacecraft, for which a relatively narrow information bandwidth is usually required; (2) real-time voice or television transmissions or rapid readout of stored data, for which wideband information capacity is required. At the same time communications from space can be categorized according to range. The usual earth orbit can be termed short range; from the vicinity of the moon involves sufficiently different problems to be called medium range; while interplanetary distances stretch our capabilities sufficiently to be called long range. These distinctions provide real constraints on the design of the appropriate communications system, since bandwidth can be traded for range and range for bandwidth, but only by added weight in the power supply, amplifier, and directive antenna can both be achieved simultaneously.

At the same time it is necessary to recognize that specific space communications requirements are oversimplified by such an analysis. Both Surveyor and Aeros, for example, will transmit picture data from medium ranges, but Aeros will be principally interested in the massive movements of clouds above the earth while Surveyor will try to obtain as sharp an image of the structure of the moon as it can. Moreover, most spacecraft seek more than a single objective and thus may have need for more than a single type of telemetry. Ranger, the Orbiting Astronomical Observatories and Geophysical Observatories, and others have specified as part of their missions the return of direct analog readings, thus adding an analog requirement where otherwise an all digital system might have been used. OAO requires a wide bandwidth for the return of optical data and also a narrow bandwidth for the spectrometer readings. Relay and Telstar retransmit wideband communications and also carry narrowband telemetry transmitters for monitoring internal temperature, voltages, sampling the radiation environment, and for acquisition and tracking.

Before discussing methods for processing and encoding data from spacecraft, it will be useful to survey the mission requirements imposed on these spacecraft. Four factors must be considered in the process of translating measurements and events at a spacecraft into a form suitable for telemetry transmission: filtering, encoding, the choice of format for this code, and the capability for decoding. Each of these requires study in the design of any telemetry system to assure the efficiency of the system, and each of these will thus be reviewed.

## 2. MISSION REQUIREMENTS

With the exception of the Mariner, all of the spacecraft presently scheduled for launch by NASA within the next year or two carry more than one means for communicating to the earth. In general, each spacecraft is equipped with a wideband link, usually to implement its primary mission, and a narrowband link, usually to transmit supplementary housekeeping or experimental data. Of the spacecraft presented in Table 1, Relay, Syncom, Tiros, and the Orbiting Astronomical Observatory follow precisely this pattern. The Rangers have three systems, one for narrowband telemetry and two for television transmission. Surveyor carries two transmitters, each capable of operation at high or low power and of using a directional or omnidirectional antenna.

As shown by Table 1, the tendency is to keep transmitter powers at 10 watts or lower, principally for the sake of reliability. Present spacecraft designs are enhancing their communication capacity over previous systems by means other than direct increases in transmitted power. All of the wideband links listed rely to some extent on antenna directivity, the last four in

Table 1. Characteristics of Spacecraft Communication Links

| | Narrowband Links | | | | Wideband Links | | | |
|---|---|---|---|---|---|---|---|---|
| | Information Rate or Bandwidth | Modulation | Trans-mitter Power | Type of Data | Information Rate or Bandwidth | Modulation | Trans-mitter Power | Type of Data |
| Mariner | 8 or 33 bits/sec | PCM/PM | 10-20 | scien-tific/engi-neering | -- | -- | -- | -- |
| Relay | 1152 bits/sec | PCM/FM | 0.25 | sci/eng | 7.5 mc | FM | 10 | TV or voice |
| Syncom | 3 kc | FM/PM | 2 | eng | 500 kc | FM/PM | 2 | voice |
| Tiros | 1 kc | AM | 0.03 | eng | 62.5 kc | FM/FM | 2 | facsimile |
| Ranger 6-9 | 3500 bits/sec | PSK/PM PAM/PM | 3 | sci/eng | 200 kc | FM | 60 | facsimile |
| OAO | 1042 bits/sec | PCM/FM | | sci/eng | 27,300 bits/sec | PCM/FM | | facsimile |
| | | | | | 62.5 kc | AM | | facsimile |
| OGO | up to 50 kc | FM | 0.5 | sci/eng | 128,000 bits/sec | PCM /PM | 4 | sci/eng |
| Surveyor | 550 bits/sec | PCM/FM PCM/PM | 0.1 | eng/sci/facsimile | 4400 bits/sec | PCM/FM | 10 | sci/eng/ |
| | | | | | 220 kc | FM | 10 | facsimile |

the table being attitude controlled in three dimensions to permit this and Relay, Syncom, and Tiros utilizing spin stabilization to assist in providing antenna gain. It is also clear that having made the choice to keep power output low has in turn placed a premium on careful use of that power.

It can be seen from Table 1 that the requirements these spacecraft have for experimental and engineering data are satisfied by information rates in the neighborhood 1 to 4 kilobits/sec. The bandwidth called for on the communication link shown for the Orbiting Geophysical Observatory is a special case of providing in this satellite a capability for handling a large number of experiments requiring analog telemetry. Other spacecraft also provide analog readout of such engineering data as temperature and voltages, but it is noteworthy that many spacecraft digitize information on the narrow-band link.[1]

A large portion of the wideband links is devoted to picture transmission. Relay is a special case, having deliberately the capability for real-time retransmission of commercial quality television, but the other spacecraft have carefully husbanded the available bandwidth by modifying picture resolution or transmittal time according to mission. The choices that have been made in these parameters are shown in Table 2. The reduced frame rate

Table 2. Spacecraft Television Parameters

| | Resolution (lines/frame) | Transmission Rate (frames/sec) |
|---|---|---|
| Tiros | 500 | 0.08 |
| Nimbus | 800 | 0.01 |
| Ranger 3-5 | 200 | 0.07 |
| Ranger 6-9 | 800 | 0.2 |
| OAO | 512 | 0.5 |
| Surveyor | 600 | 1.0 |

[1] "Data Acquisition from Spacecraft," NASA SP-16, National Aeronautics and Space Administration, Washington, Dec. 1962.

requires the earth receiver to reconstruct the picture over an extended period of time thus requiring some type of storage or memory in both the ground equipment and in the spacecraft. Ranger 6-9 and Nimbus illustrate the growth in resolution that is occurring in spacecraft missions.

Another requirement for wideband communication links is the need for rapid readout of stored data. It is occasionally not possible for a satellite to be tracked and interrogated continuously by ground stations and it is never economical. Thus provision needs to be made for the satellite data to be accumulated for a single, delayed communication. Tiros, for example, stores on tape approximately 32 pictures on each 100-minute orbit, which are transmitted during the 10 to 15 minute interrogation period. OGO has the capacity for storing data on tape for six hours, all of which can then be read out in 22 minutes. Storage in OAO, of 200,000 bits, is provided by magnetic cores.

If we look beyond these spacecraft we can foresee that communication requirements will certainly continue to expand. The Apollo mission is now planning for real-time, commercial quality television to be carried in the Lunar Excursion Module. Voyager designs now being studied for Mars and Venus missions call for picture transmission of the type now implemented for lunar ranges.

Because of the continuing limitations on spacecraft transmitter power it is clear that the effort to improve the efficiency of use of this power is a significant part of communication systems design. Most of the engineering and scientific data from contemporary spacecraft are handled by relatively narrowband links, but the requirements for storage of this data for later readout and the need for picture transmission have established a general need for a separate link of greater capacity. Since the power available for the larger bandwidths remains about the same, the greater bandwidth requires directive antennas and, just as essentially, optimum use of the channel by data processing and encoding.

## 3. FILTERING

Filtering can be extremely useful in reducing redundancy in the telemetered information. Choosing to transmit only every nth event in a sequence, every 10th cosmic ray pulse, for example, is a valuable method of filtering in those areas which are amenable to statistical understanding. Measuring the exact coordinates in space and time of every cosmic ray to hit a spacecraft sensor would provide a staggering volume of information, which on the ground would have to be evaluated statistically in any event. Accumulation in the spacecraft and transmission of the fact that some predetermined flux increment has been reached can eliminate from the telemetry a large flow of unnecessary data. Similarly if this type of statistical data is stored, it may be adequate, at readout, to transmit only three data points: a cumulative total of the flux, the peak rate and the minimum rate, together with the time associated with the maximum and minimum rates.

A second type of filtering is the scaling of information, exemplified by the method frequently employed in magnetometers. These are constructed so that their output signals are logarithmic functions of the input. In this manner the information is not saturated by the large variations in intensity of magnetic field as the magnetometer passes, for example, from the earth's field to that of space.

An adaptation of the scaling technique is that used by the triple-coincident telescope developed by the University of Chicago and carried on Pioneer 5, Rangers 1 and 2, and many other spacecraft. The instrument consists of seven radiation-detector tubes arranged in two groups of three closely packed about the seventh in the center. Packaging of the assembly is arranged so that the minimum energy of particles counted is precisely known both for the external tubes and for the central tube. A singles count from the central tube thus relays data on one energy level of radiation and if properly scaled will register about as many output counts as the triples count, which relays data on the higher energy level.

The proper selection of a threshold is a third method for obtaining selective filtering. The measurement of temperature at a given site in the spacecraft, for example, may serve to provide a warning of excessive heat and need transmit no data until a minimum temperature is reached. Radiation detectors for purposes of evaluating the potential harm in a sector of space can be shielded to eliminate the counting of the harmless, low-energy electrons.

The Orbiting Astronomical Observatory[2] makes use of this technique by designing its telemetry system to send wideband data only when the telescope has a star in sight which is emitting radiation at one of the wavelengths to which the telescope is sensitive (Figure 1). The analog video in OAO will be used primarily for qualitative viewing in real time only; a 512-line raster is scanned conventionally and transmitted by FM modulation of a subcarrier. The digital video channel provides detailed information on star intensity, wave length, and position, quantizing each of the 512 lines into 512 line segments. As the electron beam scans the raster a decision is made as to whether information is present in the line segment (i.e., a star is in view) and if so the beam is held until digital encoding of the light intensity is completed. Encoding includes coordinates of the line segment, frequency band (camera), and radiant intensity. This data is stored until the observatory passes over a ground station. The OAO thus reduces bandwidth by means of multiple filtering, first on wavelength and second on the presence of information, i.e., where no star is observed no data is sent.

Another type of limiting to reduce redundancy is the use of a data processor to limit the data transmitted to the ground to those measurements which have changed by some preselected amount since the last transmission. For example, a 10-pound unit capable of sifting 10,000 samples per second to decide which warrant transmission has been described[3] which would provide bandwidth compression of 30 to 400 to 1 depending upon the type of measurements encountered.

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[2] R.R. Ziemer, "Orbiting Astronomical Observatories," Astronautics, 6 (May 1961), 36 ff.

[3] J.R. Hulme and R.A. Schomburg, National Telemetering Conference, Washington, D.C., 1962.

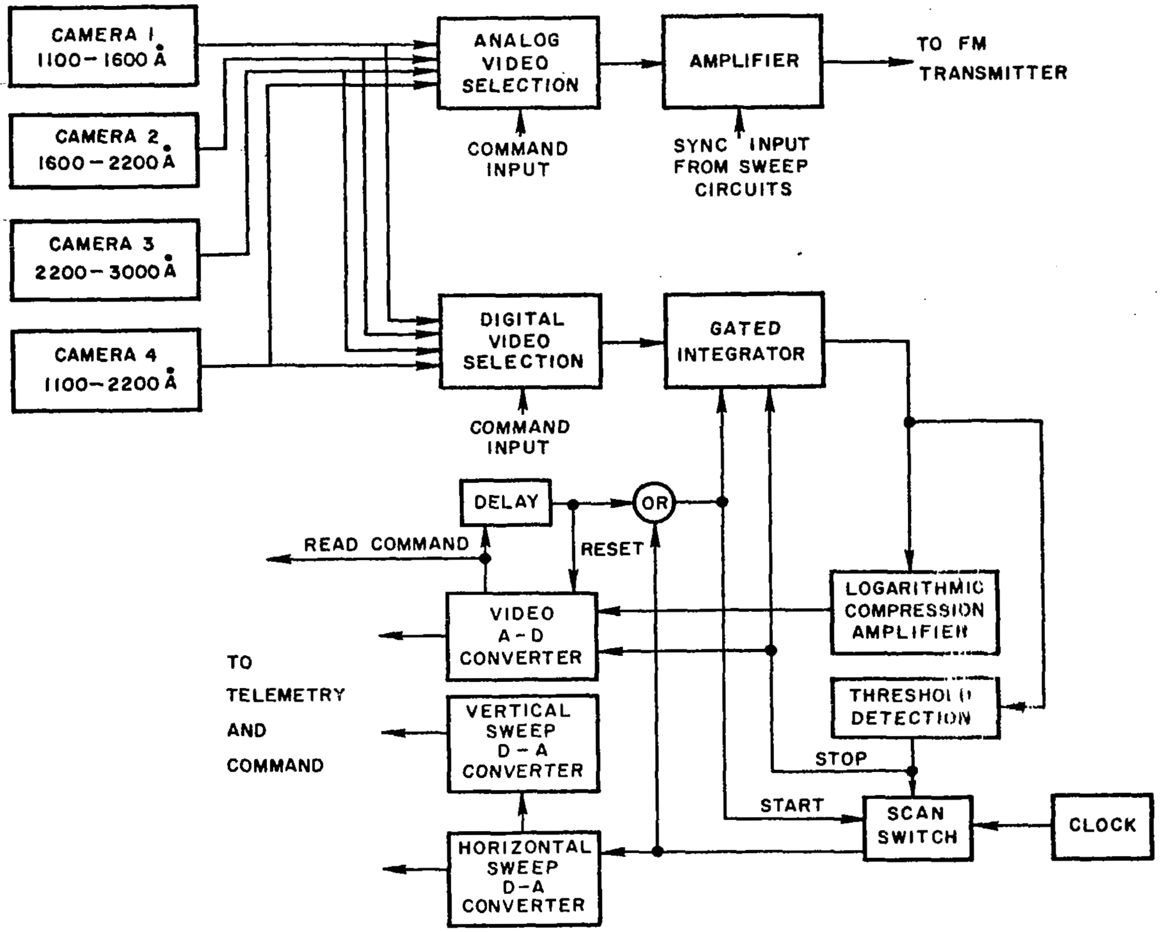


Figure 1. The Orbiting Astronomical Observatory Video System

## 4. ENCODING

The choice of the encoding techniques is as important as filtering in maximizing the efficiency of the telemetry link. Analog telemetry directly impressed either on the carrier or on a subcarrier is perhaps the simplest method of coding the time rate of change of the quantity measured into a variation in a characteristic of the carrier.

The telemetry system in the hard-landed lunar capsule in the Ranger program, for example, took advantage of the sinusoidal, low frequency nature of its seismometer payload to provide direct modulation of the subcarrier. The system (Figure 2) takes the seismometer output, 30 millivolts at 0.05 to 5 cps, and in a preamplifier provides spectrum shaping, dynamic amplitude compression, and clipping. The conditioned signal then frequency modulates the standard IRIG Channel 2 subcarrier frequency of the voltage-controlled oscillator. This FM subcarrier in turn phase modulates the 960-Mc carrier.[4]

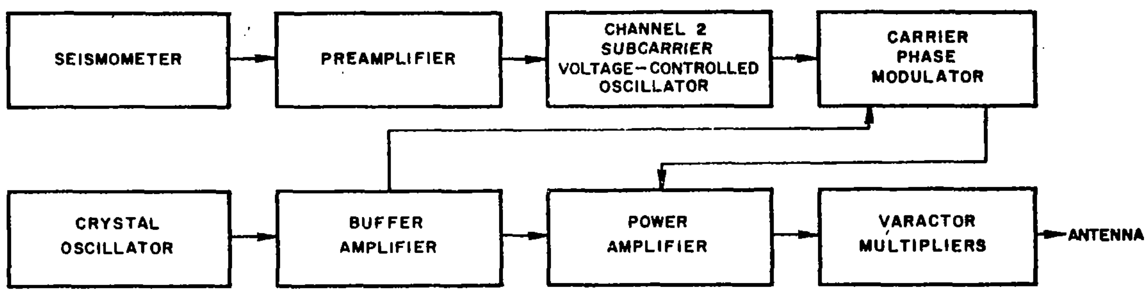


Figure 2. Ranger Seismometer Capsule Telemetry System

For the other data systems of Ranger 3-5 some encoding sophistication was required for handling up to about 85 engineering and scientific measurements on nine data channels in a 3.5-kc information bandwidth. The system (Figure 3) used frequency multiplexed subcarrier oscillators, with solid state commutator circuits and magnetic latching relay subcommutators for sequencing the data onto the subcarriers. Data in analog form was applied directly to the input of voltage-controlled oscillators at the appropriate IRIG channel frequency. Digital data was telemetered in binary form by the use of a switched two-state subcarrier oscillator. PAM input to three channels required the introduction of a rate limiting signal conditioner before subcarrier modulation to optimize the phase lock demodulation.

[4] N.A. Renzetti and B.J. Ostermier, "Communications with Lunar Probes," Jet Propulsion Laboratory Technical Report 32-148, August 23, 1961.

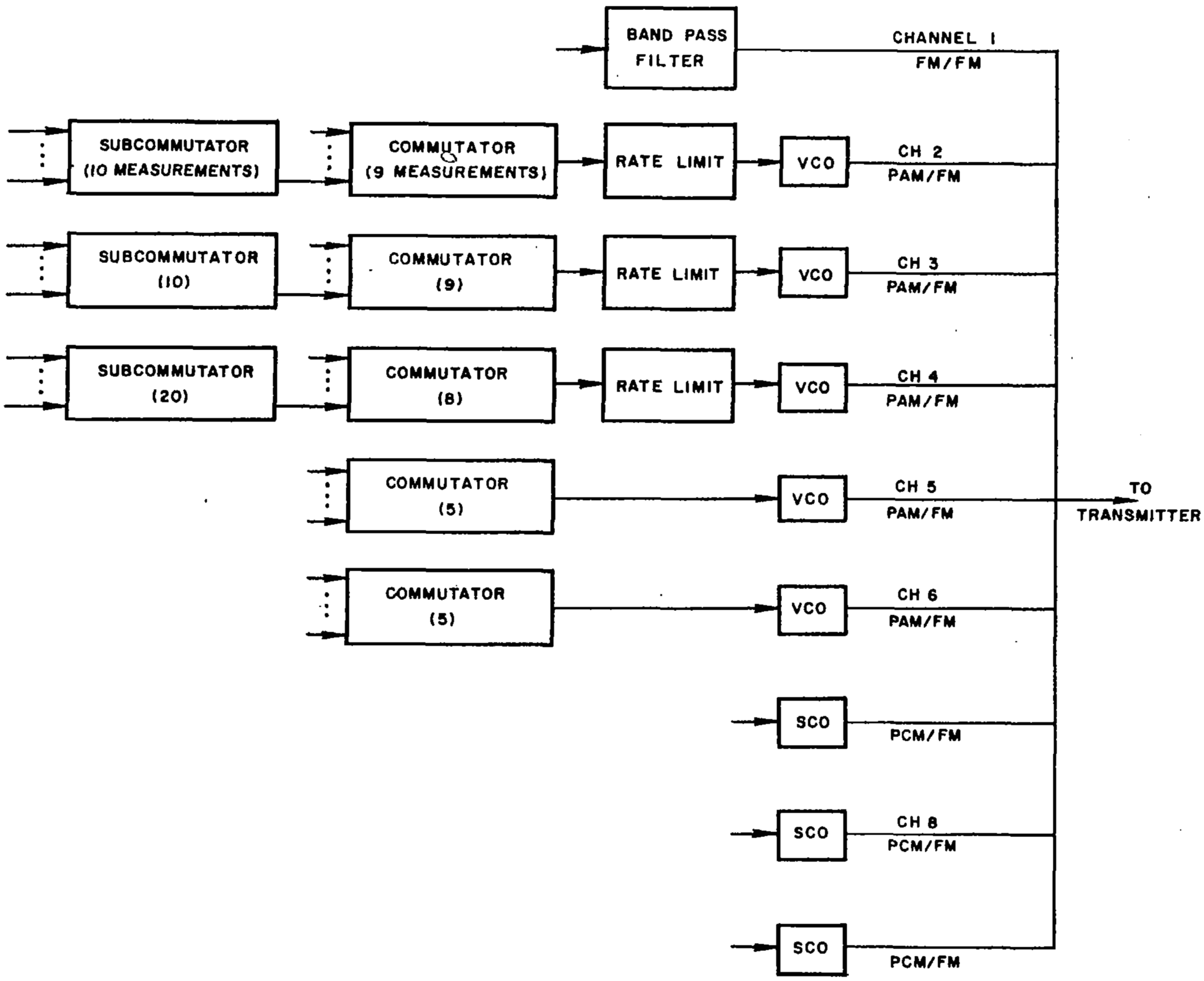


Figure 3. Ranger 3-5 Telemetry System

In favor of analog encoding is the simplicity inherent in such direct use of the sensor's output and the reliability possible with analog circuits, resulting in part from the many years of effort devoted to their development. To implement an analog system in spacecraft the basic approach has been to employ subcarrier oscillators, as just exemplified, each modulated by the output of a sensor providing the information to be telemetered. These subcarriers in turn are used to modulate the main carrier. After transmission to the ground they are separated at the receiver by discriminators. One of the disadvantages of analog encoding occurs in very long range transmissions. Since the ground discriminators' tracking will depend on maintaining a relatively low ratio of modulation to information rate, the demands placed on the stability of the subcarrier oscillator are extremely high. As information rate necessarily drops with range to maintain an adequate S/N, the percentage of subcarrier deviation due to the modulation will drop and the stability requirements on the subcarrier will rise. As a practical problem, then, for extremely long ranges when the signal rate must drop to the order of 1 cps, we do not have subcarrier oscillators whose long-term stability is sufficient to permit reliable discrimination on the ground.

One of the advantages of a digital system is the fact that the information rate can be reduced as a function of increasing range almost without limit. Other advantages of digital systems have led to their adoption for shorter ranges. These include the ease and accuracy with which telemetry can be retransmitted and reduced after reception. Digital systems also lend themselves to the practical implementation of block coding or word correlation techniques, which require less power to transmit at a given information rate than other encoding systems.[5]

Three methods of modulating a carrier with binary-coded digital data have been implemented: amplitude modulation, frequency shift keying, and phase shift keying. In spacecraft, however, AM has not been used and between FSK and PSK, the second is more general. In the last case a subcarrier is usually biphase modulated, that is, the subcarrier is shifted 180 degrees as a function of the binary information; each shift either indicates a change from 0 to 1 or from 1 to 0 from the preceding bit, or else each phase angle 0 or 180 degrees represents respectively a 0 or a 1. Whether the form involves phase changes or absolute phase it can be coherently

[5] R.W. Sanders, "Communication Efficiency Comparison of Several Communication Systems," Proc. IRE, 48 (April 1960), 575.

demodulated by a receiver using a phase-locked oscillator, but an advantage of encoding by phase changes is that demodulation can be effected without a reference oscillator, although at a slight penalty of effective S/N.

Since input information is band-limited and transmission power is at a premium, it is clear from Shannon's theorem that bandwidth expansion or spread spectrum modulation methods are the most efficient for wideband telemetry. Such methods are readily implemented and for wideband systems this conclusion has led spacecraft systems to narrow the field of modulation techniques to two: frequency modulation and pulse code phase modulation, since in both cases bandwidths can be traded for power. In view of channel efficiency and thus of power requirements there is little difference between FM and PCM/PM for wideband telemetry transmission.

For wideband FM, as employed, for example, by Relay, the necessary carrier bandwidth is given approximately by

$$B = 2f(1 + M)$$

where $f$ = the highest information frequency

$M$ = the modulation index of concern, for example, 1.8 in Relay.

If we examine a television transmission on an FM link as an example of the type of information to be transmitted over wideband links, for a typical commercial grade of picture quality (4-Mc channel capacity),

$$B = 2 \times 4(1 + 1.8)$$
$$= 22.4 \text{ Mc}$$

and since the output S/N $\approx$ 40 db the receiver input signal to noise will be about 27 db.

For PCM, for example in the system used by OAO, the video waveform is coded into a series of binary digits, a word representing a particular voltage level of the video signal. For binary-coded video, if one assumes the signal is band-limited to $f_m$ cps, the sampling theorem shows that the signal must be sampled at least every $f_m/2$ seconds. In addition, it is normally assumed for adequate picture quality that each such sample should be capable of measuring some 64 levels,[6] which corresponds to a six-bit binary code. The bit rate for television is thus:

$$H = 12 \times 4 \times 10^6 = 48 \times 10^6 \text{ bits/sec}$$

The RF bandwidth needed to carry the digital code is at least in this case 24 Mc and may be widened to improve the output S/N ratio according to Shannon's formula.

Tolerable error rate for television is normally taken as one level (word) in every picture frame.[7] In a frame (1/30 second) there will be $48 \times 10^6/6 \times 30 = 2.7 \times 10^5$ words. Thus if one word per frame is in error, $p_{we} = 4 \times 10^{-6}$, from which $p_{be} \cong 10^{-6}$. As can be seen from Figure 4 this corresponds to a required S/N at the decision circuit in the receiver of about 13 db.[8]

The need for six bits per sample has stemmed from the establishment of false contours by fewer quantization levels, i.e., spurious edges in the picture as sudden jumps from one encoding level to another occur, as illustrated in Figure 5. A digital format modified to minimize false contouring thus can permit fewer bits per sample. Delta, or differential, modulation is the most nearly proved of these techniques.[9] This system in effect transmits the intensity difference between successive picture elements rather than the entire

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[6] R. L. Carbrey, "Video Transmission Over Telephone Cable Pairs by Pulse Code Modulation," Proc. IRE, 48 (Sept. 1960), 1546.

[7] M. Schwartz, Information Transmission, Modulation, and Noise, New York 1959.

[8] See also E.F. Smith, "Attainable Error Probabilities in Demodulation of Random Binary PCM/FM Waveforms," IRE Trans. on Space Electronics and Telemetry, SET-8 (Dec. 1962), 290.

[9] C.C. Cutler, "Predictive Quantizing of TV Images," IRE Wescon Convention Record, Part 4, p. 147, Aug. 1958; J.C. Balder and C. Kramer, "Video Transmission by Delta Modulation Using Tunnel Diodes," Proc. IRE, 50 (April 1962), 428.

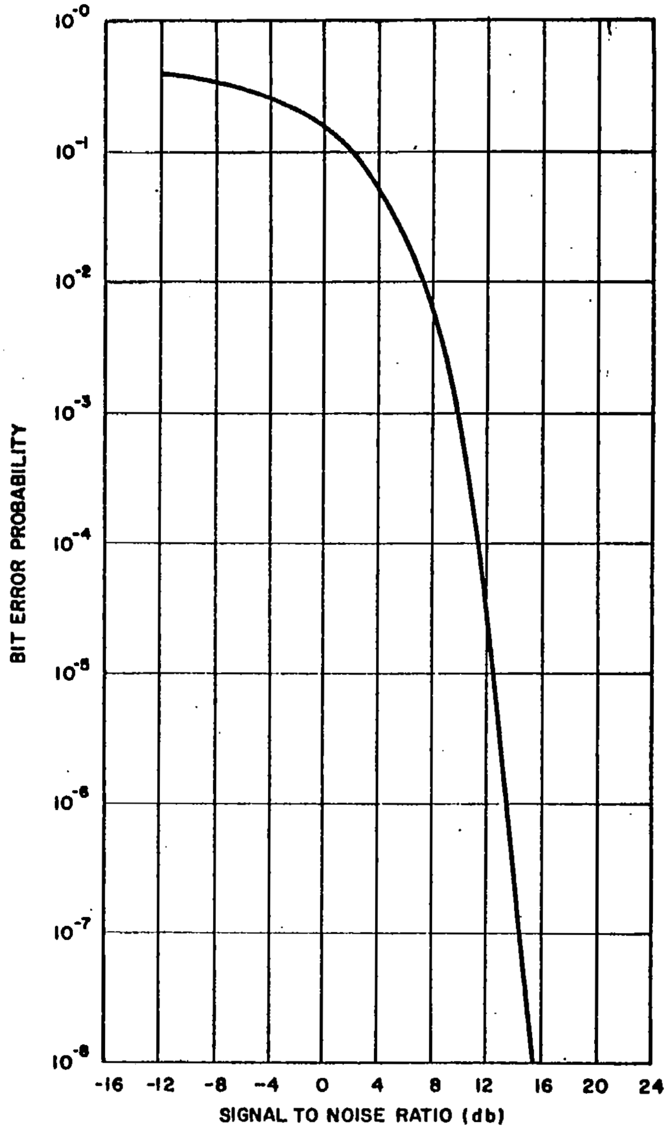
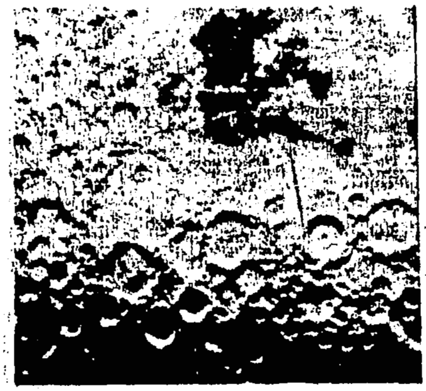
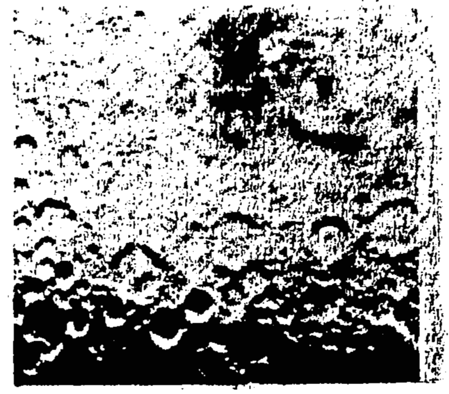



**Figure 4.** Bit Error Probability vs Peak Signal-to-Noise Power at the Decision Time, for PCM

element anew each frame. The differential nature of delta modulation, however, makes it more sensitive to noise errors so that reduced bit rate tends to be countered by more stringent demands on tolerable error rate.



2 BITS STRAIGHT PCM



6 BITS STRAIGHT PCM

Figure 5. Development of False Contours in Lunar Images

Another successful method[10] uses a pseudo-random noise generator before transmission to randomize the average level of the video signal, the noise being removed at the receiver by a second pseudo-noise generator synchronized to that at the transmitter. A third method separates the picture data into two areas, picture edges and slowly-varying tones, sending the former at a high sampling rate and the latter at a low rate.[11]

All of these systems add weight and circuit complexity to the spacecraft, which needs to be balanced against the use of an equal weight being placed in a transmitter of greater power to handle the larger bandwidths entailed by the greater bit rates. At the present time it does not appear that reducing the sampling rate at the spacecraft is practical by these means.

It is of course possible to reduce bandwidth requirements by simply reducing the resolution of the picture; reducing the line structure by half results in a reduction in required channel capacity by about one-fourth, other things remaining equal. For spacecraft, however, practical methods

[10] L. G. Roberts, "Picture Coding Using Pseudo-Random Noise," IRE Trans. on IT, 8 (Feb. 1962), 145.

[11] W. F. Schreiber et al, "Synthetic Highs--An Experimental TV Bandwidth Reduction System," J. Soc. Motion Picture and Television Engineers, 68 (1959), 525; F.A. Gicca, "Spacecraft Digital Television," Air Force Association National Convention, Las Vegas, 1962.

do exist for reducing bandwidth requirements while at the same time retaining resolution, either by reducing picture size or rate, or both. The television system for Ranger 3-5 employs a video bandwidth of only 2 kc. It achieves its bandwidth reduction by using a 200-line picture, 13 seconds for transmitting one frame, and computer reconstruction of the picture on the earth. In operation, an image is shuttered onto the faceplate of the vidicon camera for 20 milliseconds and the slowly decaying image scanned at a rate which covers the frame in 10 seconds. This sweep is followed by a 3-second erasure (during which time the same channel was programmed for use by the 25 bits/sec PCM/FM gamma-ray telescope telemetry). Picture reconstruction at the ground required recording the received signal on magnetic tape, converting it into digital form, and re-recording it on computer input tape for photo reconstruction.

Reduction of bandwidth by means of reduction of the size of picture transmitted is illustrated by the Ranger 6-9 system (Figure 6).[12] Six one-inch vidicon cameras are carried. Of these, two are fully scanned, providing a resolution of 800 lines over a tube format of 0.44 by 0.44 inch, with a side field coverage of 8.4 degrees. A reduced raster is used by four of the six cameras scanning a 0.11 by 0.11-inch central portion of the tube at about the same line density, to produce a 200-line picture with the same resolution. The side field of view is 2.1 degrees. A long-persistence vidicon tube is required, in that the camera shutter is open for only 80 milliseconds for each picture. The full-field camera scans for 2.56 seconds, followed by an identical erasure period. One frame thus takes 5.12 seconds. While one camera is scanning the other erases. The four limited-field cameras transmit one picture in 0.84 second, 0.2 second for scanning and 0.64 for erasure while the other three scan.

The resolution and frame rate for the Ranger 6-9 system is substantially greater than that of the Ranger 3-5, total bandwidth requirement, however, for pictures of nearly 40 per cent better resolution than commercial television

[12] F.M. Riddle et al, "JPL Contributions to the 1962 National Telemetry Conference," JPL Technical Memorandum 33-88, May 21, 1962.

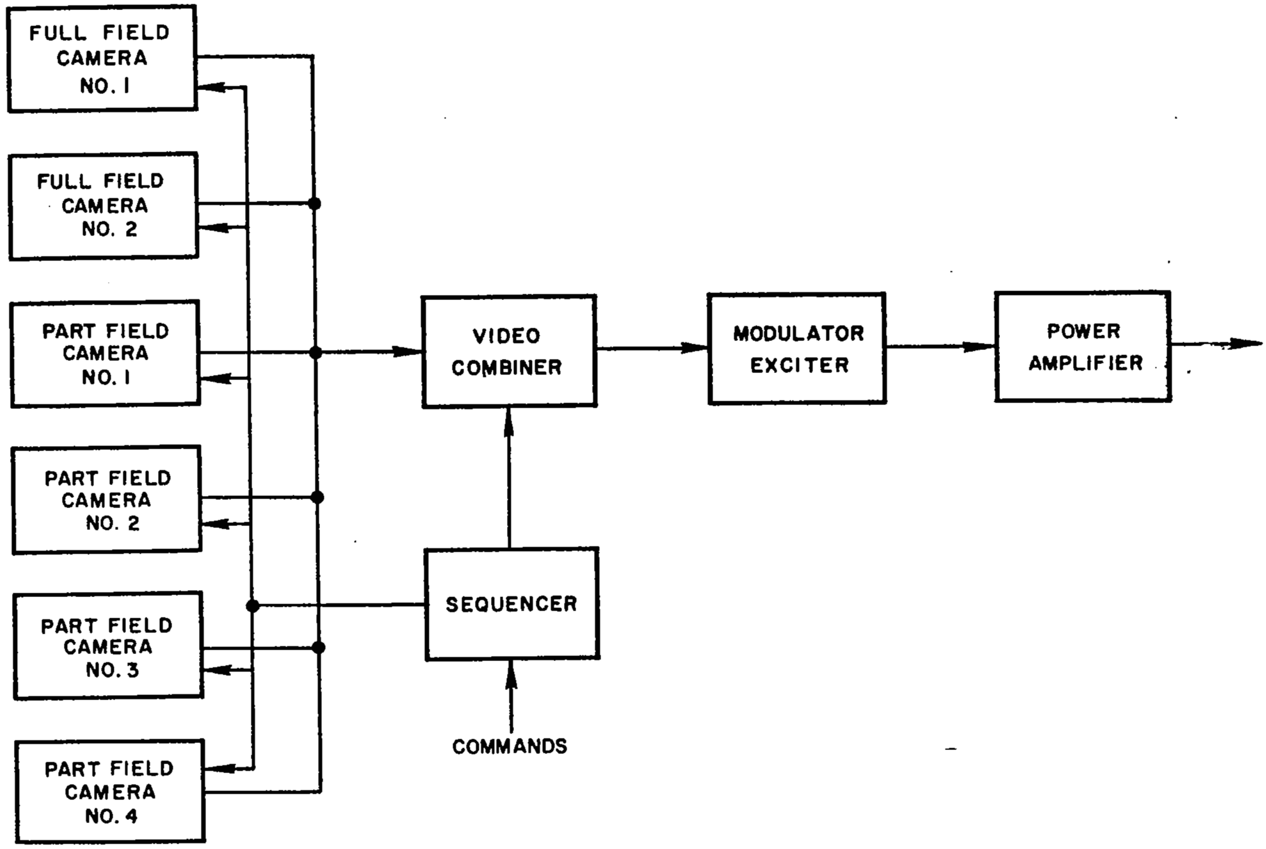



Figure 6. Ranger 6-9 Video Telemetry System

is less than for commercial television because of the slower frame rate and the reduced picture size of four of the six cameras. Sequencing and timing is such that all the video data is transmitted in a steady bandwidth of 200 kc.

The bandwidth for voice transmission is not subject to reduction in such a fashion, primarily because a part of the psychological value of voice messages would be lost if real-time transmission was not used. The voice channel could be more efficiently coded. For example, if one is willing to put up with a synthetic, mechanized voice, the method known as formant tracking can transmit a voice channel in real time at 1000 bits/sec and, in theory at least, this can be reduced to 60 bits/sec by means of automatic phonetic coding.[13] The formant tracking as now implemented derives a set of seven frequency ranges from the original voice signal which are digitized into a 23-bit word sampled at a 43.5-cps rate to provide a 1000 bits/sec serial digital stream. Here, as in the case of video, the use of these bandwidth-reduction techniques entails, in practical application, reasonably complex circuits and this mitigates against their use in spacecraft applications. Thus at present a bandwidth of 3 or 4 kc is used for voice transmission.

## 5. DECODING

Proper translation on the ground of a digital telemetry frame into its constituent words requires the presence of synchronizing symbols which a decoder or computer can recognize. For example, a standard practice is to make the first pulse of every word a zero and use it to signal the beginning of the word. This sync is ambiguous, however, since it requires counting from the last frame sync symbol. A standard frame sync symbol is the making of the first word of every frame all ones. (See Figure 7.) A frame sync symbol which in addition to identifying each frame also unambiguously identifies the beginning of each word would permit the word sync pulses to be used instead to carry information. A method for determining such a code has been described by Barker.[14] The minimum number of digits required for this code is a function of four system variables: the probability that a synchronizing code is correctly sent, the probability of transmission error, the probability of correct response at the receiver to the code, and the maximum probability of random false synchronization. Analytic methods for calculating these variables are given by Barker. If we assume optimum values for these variables, a considerable gain (Figure 8) in the density of information permitted for a given binary

[13] S. J. Campanella, "A 1000 Bit Per Second Speech Compression System," Fifth National Symposium on Global Communications, Chicago, May 1961, p. 265; J.R. Pierce, Symbols, Signals and Noise, New York, 1961, pp.125-144.

[14] S.N. Barker, "Group Synchronization of Binary Digital Systems," Communication Theory, ed. by W. Jackson, London, 1953; D.G. Luenberger, "On Barker Codes of Even Length," Proc. IEEE, 51 (January 1963), 230.

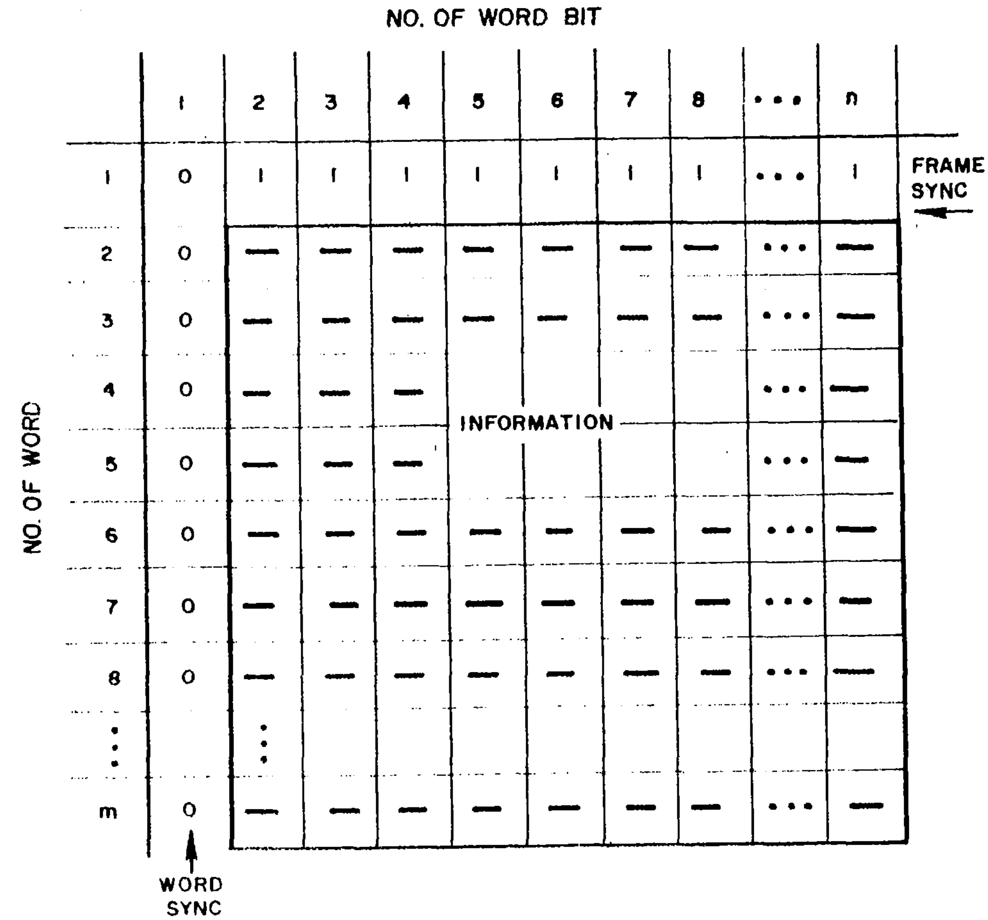



Figure 7. Word and Frame Sync in Digital Format

format is possible, particularly those formats with many words in each frame. Barker codes are being incorporated in telemetry systems now being designed; the Pioneer series now planned for flight during the International Quiet Sun Year will very likely use such a code.

If the data to be transmitted varies quite rapidly with time or if the data is subject to large, discontinuous fluctuations, an additional percentage of the encoding may be required for error detection. Whether this is actually required will of course depend upon the anticipated possible fluctuations of the data with respect to the bit error probability of the system. Error

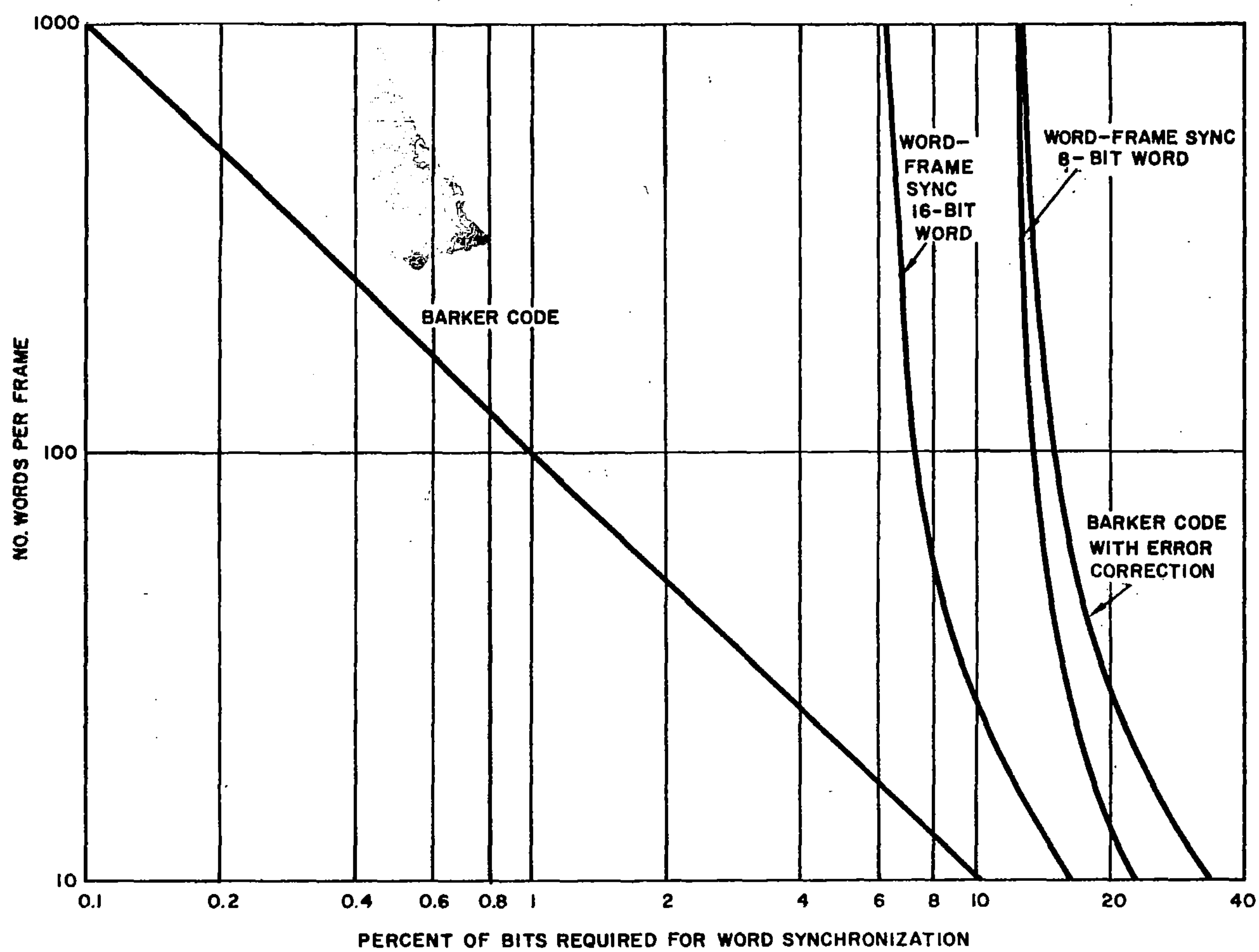



Figure 8. Requirement for Digital Word Synchronization as a Function of Frame Length

detection will normally require only one bit per word as a parity check. If, further, it is desired to incorporate the capability for correction of errors as well as their detection the total number of bits required to check information will be m + n, to provide vertical parity checks in the frame as well as horizontal. These percentages are plotted as a function of length of the frame in Figure 8. The facts that circuits needed to generate parity bits considerably complicate the encoding circuitry and that telemetry information normally has intrinsic redundancy adequate for error correction, assuming a probability of bit error low enough to make the redundancy recognizable, make it usually not desirable to incorporate the capacity for error correction.

## 6. FORMAT

In digital subsystems, the format into which the information is encoded must result from the synthesis of the constraints imposed by the requirements for filtering, encoding, and decoding. Inasmuch as these constraints vary, depending upon the particular phase of any mission, the ability to change the format while the spacecraft is in flight is desirable. The factors of importance in the selection of a format include the choice of word length, the number of words, the assignment of words to particular functions, and the multiple use of a given word, for example in subcommutated words. The encoding of the information into a format uses logic circuitry generally called the format sequencer.

The choice of word length will be determined by the number of bits required to carry the largest anticipated binary number. The larger the word, of course, the more complex the data handling equipment may be, but, as we have just seen, the more efficient the format can be from the point of view of data recognition. Measurements which do not require the full word length can then share words. The number of words in a frame is also determined by the requirements of the telemetry; what measurements must be sent frequently, what need be sent only infrequently, what require full words, and what require particular fractions of words must all be weighed in the determination of the format.

The proper design of format will represent the combination of all of these factors in a logical form which prevents the waste of transmitted bits and which keeps redundancy at a level no more than is useful. In the adaptation of the narrowband digital telemetry system for Explorer 6 and Pioneer 5, for example, the telemetry systems were very much alike except that distinct formats were found optimum for the different configurations, including trajectory, transmission times, and other mission variables.[15] These formats, illustrated in

[15] G. E. Mueller, "Pioneer 5 and Explorer 6, Systems Engineered Space Probes," Proc., XIth International Astronautical Congress, Stockholm, 1960, vol. I.

Figure 9, subcommutated those slowly varying measurements which did not need to be read out on each frame, used subdivision of words when the

| | | BIT NUMBER | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WORD NUMBER | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| FRAME SYNC. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 0 | 1 | PROPORTIONAL COUNTER, TRIPLE COINCIDENCE | | | | | | | | | |
| | 2 | 0 | 1 | PROPORTIONAL COUNTER, SINGLE INCIDENCE | | | | | | | | | |
| | 3 | 0 | 1 | HIGH MOMEN. MICROMET. | | | TOTAL MICROMETEORITE | | | | | | |
| | 4 | 0 | 1 | GEIGER – MUELLER COUNTER | | | | | | | | | |
| | 5 | 0 | 1 | IONIZATION CHAMBER | | | | | | | | | |
| | 6 | 0 | 1 | SCINTILLATION COUNTER | | | | | | | | | |
| | 7 | 0 | 1 | SEARCH COIL AMPLITUDE | | | | | | SEARCH COIL PHASE | | | |
| | 8 | 0 | 1 | FLUX GATE MAGNETIC FIELD | | | | | | FLUX GATE RANGE | | | |
| | 9 | 0 | 1 | VLF | | | | | | 1 | 1 | 1 | 1 |
| | 10 | 0 | 1 | SUBCOMMUTATOR | | | | | | SUBCOM. CHANNEL NO. | | | |

EXPLORER VI

| | | BIT NUMBER | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WORD NUMBER | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| FRAME SYNC. | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 1 | 0 | 1 | PROPORTIONAL COUNTER, TRIPLE COINCIDENCE | | | | | | | | | |
| | 2 | 0 | 1 | PROPORTIONAL COUNTER, SINGLE INCIDENCE | | | | | | | | | |
| | 3 | 0 | 1 | HIGH MOMEN. MICROMET. | | | TOTAL MICROMETEORITE | | | | | | |
| | 4 | 0 | 1 | GEIGER – MUELLER COUNTER | | | | | | | | | |
| | 5 | 0 | 1 | IONIZATION CHAMBER | | | | | | | | | |
| | 6 | 0 | 1 | SEARCH COIL AMPLITUDE | | | | | | SEARCH COIL PHASE | | | |
| | 7 | 0 | 1 | SUBCOMMUTATOR | | | | | | SUBCOM. CHANNEL NO. | | | |

PIONEER V

Figure 9. Digital Frame Structure

measurement did not require the full number of bits available in a word, and time-sequencing of the measurements carried in a portion of a word when the measurement had validity only at specific times during the mission. The digital formats for narrowband telemetry systems on other spacecraft have been quite similar.

By contrast, efficient use of the binary format for wideband communications must be considerably more complicated. The Orbiting Astronomical Observatory, which transmits at about 30,000 bits/sec, uses a format of 4096 words of 25 bits each. The Surveyor formats change quite substantially as the spacecraft passes through the various phases of its mission; these range from 16 to 100 11-bit words at rates from 550 to 4400 bits/sec. The Orbiting Geophysical Observatory,[16] which transmits at rates up to 128,000 bits/sec, uses a format of 128 nine-bit words, illustrated in Figure 10. As shown, 12 words are used for the specific functions of synchronization (words 1, 2, 3), timing (33, 34, 35), mode identification (65, 66, 67), and the subcommutated data (97, 98, 99). The remaining words are used for experiment data and may read analog data or digital data as required. A number of the words may be switched between analog or digital data as required. Word subcommutation is illustrated in Figure 11, which shows the spacecraft subcommutator No. 1 format (word 98 in the main format). This subcommutator is assigned for housekeeping measurements (spacecraft temperature, voltages, etc.) and has 88 analog and 10 digital dates. The remaining slots are used for supercommutation of analog measurements. This word 98 can be run at the main frame rate on command so that during launch or other critical periods during the spacecraft lifetime the telemetry emphasis can be shifted from experimental data to spacecraft data.

## 7. CONCLUSION

This review of present space communication systems and techniques leads to the following conclusions:

[16] P.F. Glaser and E.R. Spangler, "The Orbiting Geophysical Observatory," Electronics, 36 (Feb. 15, 1963), 61-65.

| | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 SYNCH | 2 RONIZATION | 3 WORDS | 4 A | 5 A | 6 A | 7 A | 8 A | 9 D | 10 D/A | 11 D/A | 12 D/A | 13 A | 14 A | 15 A | 16 A |
| 17 D | 18 D | 19 D | 20 D/A | 21 A | 22 A | 23 A | 24 A | 25 D | 26 D/A | 27 D/A | 28 D/A | 29 A 0 | 30 A | 31 A | 32 A |
| 33 ACCU | 34 MULATED TIME | 35 (SECS.) UNUSED | 36 A | 37 A | 38 A | 39 A | 40 A | 41 D | 42 D/A | 43 D/A | 44 D/A | 45 A | 46 A | 47 A | 48 A |
| 49 D | 50 D | 51 D | 52 D/A | 53 A | 54 A | 55 A | 56 A | 57 D | 58 D/A | 59 D/A | 60 D/A | 61 A | 62 A | 63 A | 64 A |
| 65 IDEN DATA BEING SUB-COMMUTATOR POSITION | 66 TIFICATION EXAMINED MODE FLEXIBLE FORMAT NO. | 67 WORDS DATA NOT EXAMINED MODE FLEXIBLE FORMAT NO. | 68 A | 69 A | 70 A | 71 A | 72 A | 73 D | 74 D/A | 75 D/A | 76 D/A | 77 A | 78 A | 79 A | 80 A |
| 81 D | 82 D | 83 D | 84 D/A | 85 A | 86 A | 87 A | 88 A | 89 D | 90 D/A | 91 D/A | 92 D/A | 93 A | 94 A | 95 A | 96 A |
| 97 EXPERIMENT SUB-COMMUTATOR | 98 SPACECRAFT SUB-COMMUTATOR NO. 1 | 99 SPACECRAFT SUB-COMMUTATOR NO. 2 | 100 A | 101 A | 102 A | 103 A | 104 A | 105 D | 106 D/A | 107 D/A | 108 D/A | 109 A | 110 A | 111 A | 112 A |
| 113 D | 114 D | 115 D | 116 D/A | 117 A | 118 A | 119 A | 120 A | 121 D | 122 D/A | 123 D/A | 124 D/A | 125 A | 126 A | 127 A | 128 A |

D = DIGITAL EXPERIMENT
A = ANALOG EXPERIMENT
D/A = DIGITAL OR ANALOG EXPERIMENT

Figure 10. Main Frame Format in OGO

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 A/1 | 2 A/2 | 3 A/3 | 4 A/4 | 5 A/5 | 6 A/6 | 7 A/7 | 8 A/8 |
| 9 A/9 | 10 A/10 | 11 A/11 | 12 A/12 | 13 A/13 | 14 A/14 | 15 A/15 | 16 A/16 |
| 17 A/17 | 18 A/18 | 19 A/19 | 20 A/20 | 21 A/21 | 22 A/22 | 23 A/23 | 24 A/24 |
| 25 A/25 | 26 A/26 | 27 A/27 | 28 A/28 | 29 A/29 | 30 A/30 | 31 A/31 | 32 A/32 |
| 33 A/33 | 34 A/34 | 35 A/35 | 36 A/36 | 37 A/37 | 38 A/38 | 39 A/39 | 40 A/40 |
| 41 A/41 | 42 A/42 | 43 A/43 | 44 A/44 | 45 A/45 | 46 A/46 | 47 A/47 | 48 A/48 |
| 49 A/49 | 50 A/50 | 51 A/51 | 52 A/52 | 53 A/53 | 54 A/54 | 55 A/55 | 56 A/56 |
| 57 A/57 | 58 A/58 | 59 A/59 | 60 A/60 | 61 A/61 | 62 A/62 | 63 A/63 | 64 A/64 |
| 65 A/65 | 66 A/66 | 67 A/67 | 68 A/68 | 69 A/69 | 70 A/70 | 71 A/71 | 72 A/72 |
| 73 A/9 | 74 A/10 | 75 A/11 | 76 A/12 | 77 A/13 | 78 D | 79 D | 80 A/16 |
| 81 A/73 | 82 A/74 | 83 A/75 | 84 A/76 | 85 A/77 | 86 A/78 | 87 A/79 | 88 A/80 |
| 89 A/25 | 90 A/26 | 91 A/27 | 92 A/28 | 93 A/29 | 94 D | 95 D | 96 D |
| 97 A/81 | 98 A/82 | 99 A/83 | 100 A/84 | 101 A/85 | 102 A/86 | 103 A/87 | 104 A/88 |
| 105 A/41 | 106 A/42 | 107 A/43 | 108 A/44 | 109 A/45 | 110 D | 111 D | 112 A/48 |
| 113 A/49 | 114 A/50 | 115 A/51 | 116 A/52 | 117 A/53 | 118 A/54 | 119 A/55 | 120 A/56 |
| 121 A/57 | 122 A/58 | 123 A/59 | 124 A/60 | 125 A/61 | 126 D | 127 D | 128 D |

A/1 = ANALOG GATE NO. 1
D = DIGITAL GATE

Figure 11. The OGO Spacecraft Subcommutator No. 1 Format

1) The requirement for low power transmitters in spacecraft places a premium on efficient use of the power that is transmitted.

2) Substantial benefits in achieving this efficiency are possible by means of information processing in the spacecraft, in particular the use of filtering, such methods as Barker codes for data recognition, and the careful planning of digital frame formats.

3) For narrowband, long range telemetry digital encoding appears desirable. For wideband transmission either analog FM or digital encoding appears equally satisfactory.

4) Sophisticated techniques for reducing bandwidth requirements for voice and television do not appear practicable for spacecraft at present, but considerable savings in television bandwidth can usefully be achieved for space missions by reducing the resolution and frame rate.